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Both the experimental and field phases of the project indicate that geomorphic thesholds exist and that this concept can be of significance in the recognition of incipiently unstable, components of the landscape. For example, within a given region, valley floor slopes, alluvial fan slopes and channel sinuosity usually vary over an order of magnitude. It should be possible to identify at what range of slopes the landforms are unstable and subject to major erosional or depositional change, as a result of a triggering hydrologic event or due to man's intervention. → next page

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Abstract continued:

cont

The results of this project should have a significant contribution to make not only in the development of preventive conservation but also to river control engineering. The geomorphic approach requires an understanding of landform history, which can provide a basis for working with the natural system in order to accomplish conservation or river stability goals.

An Experimental Study of
Geomorphic Thresholds

FINAL REPORT

S. A. Schumm

1 April, 1977

U. S. Army Research Office

Grant DAHC04-74-G-0020

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CONTENTS

An Experimental Study of Geomorphic Thresholds

Introduction

Utilizing a unique research facility, experimental studies of alluvial fan and drainage system development were performed to test the hypothesis that geomorphic thresholds exist (Schumm, 1973) and that they exert a significant influence on the erosional and depositional evolution of landforms. These thresholds of landform stability produce sudden and dramatic reversals of the erosional and depositional processes without any major external stimulus (tectonism, climate change, etc.). It was assumed that these reversals would be observable and predictable and that they would be expressed both as variations in the rate of sediment delivery and as recognizable stratigraphic and sedimentologic variations in the resulting depositional record. Recognition of such threshold conditions during the experiments could lead to the development of geomorphic criteria for the identification of some potentially unstable landforms in nature.

The alluvial fan and its source area drainage basin was selected as the geomorphic system to be tested experimentally because it consists of clearly defined erosional and depositional components. In addition, it is essentially a closed system with relatively little loss of sediment. These characteristics were ideal for the experimental study.

Experimental Studies and Results

Fluvial (wet) fans

During the first series of experiments the Drainage Evolution Research Facility (DERF) served as an experimental area in which the growth of a "wet" or fluvial fan under constant conditions of sediment and water discharge was documented. The DERF is a 15.3 m long by 0.2 m wide by 2 m deep container enclosed in a prefabricated steel building. Twelve elevated sprinkler units mounted along the walls provide constant simulated precipitation to the enclosed area at intensities ranging from 10 to 100 mm/hr with a drop size distribution roughly equivalent to natural rainfall intensity of 15 mm/hr.

A silt-sand mixture was placed in the upper or western half of the container to a depth of nearly 2 meters. This 52 square meter area was graded and slightly compacted into a symmetrical, slightly concave basin which became the sediment source area for the experimental fan. The lower half of the DERF was then leveled to receive the material eroded from the source area (figure 1). Precipitation was applied to the drainage basin at a constant rate of 5 cm/hr throughout the experiment.

Analysis of over 450 measurements of sediment discharge taken at ten minute intervals and sampled at the outlet of the developing drainage network confirm previous findings by Parker (1977, unpublished Ph.D. dissertation) that an exponential decrease in sediment yield occurs with time during the erosional evolution of a drainage system under constant hydrologic conditions. However, after this significant decrease to an "average" sediment yield, cyclic variations of sediment yield were measured (figure 2). These variations appear to be due to storage and flushing of sediment from the valleys of the sediment source area. It was not possible to study the cause of these variations because the experimental procedure required that a run be continued for a designated period of time in order to obtain convincing evidence for geomorphic thresholds and their influence on alluvial fan growth, but later experiments were performed to investigate this phenomenon.

Periodic adjustment of the fan surface in response to the decreasing sediment yields was accomplished by incision of the mid-fan and upper-fan

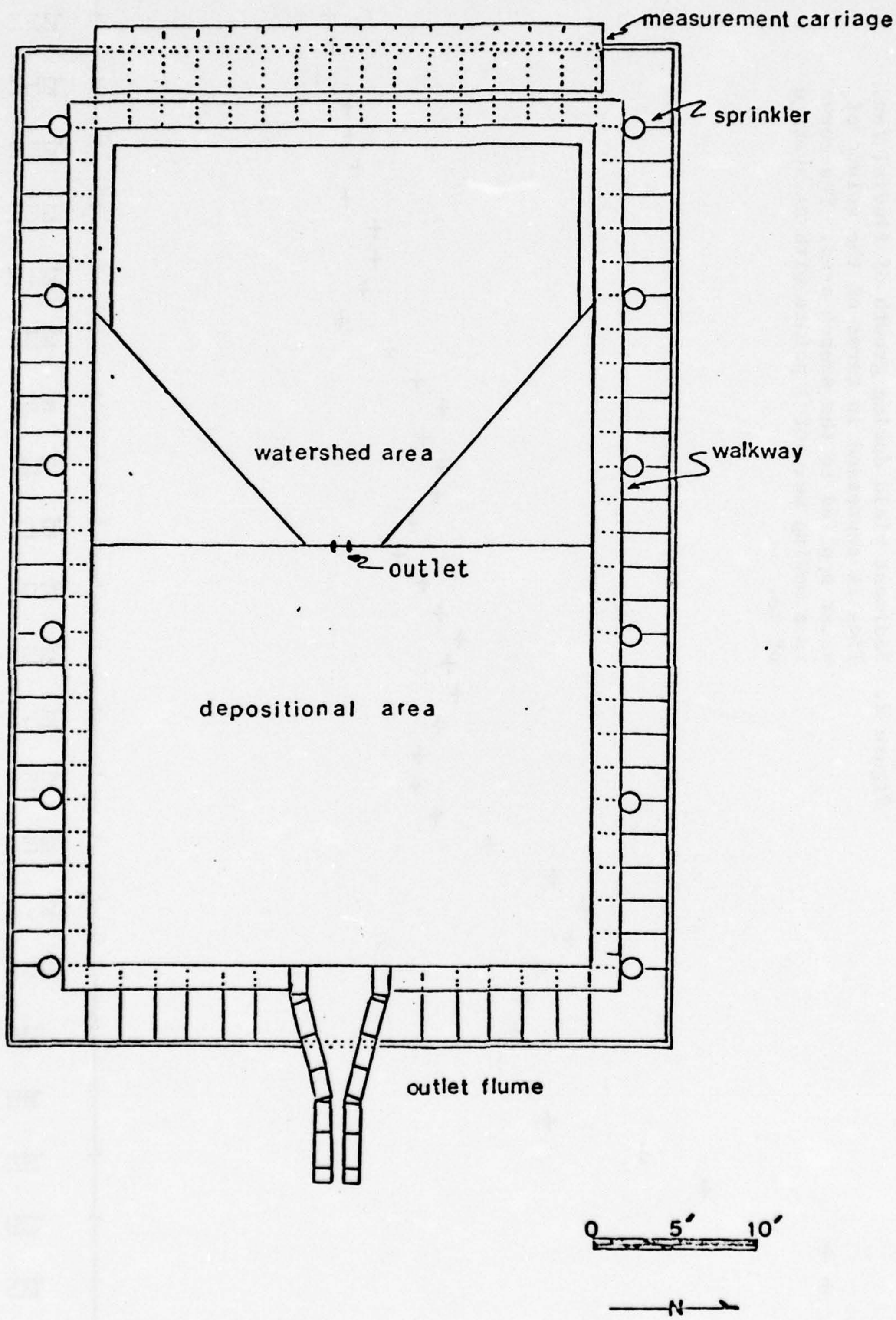

Figure (1) Plan view of the research facility.

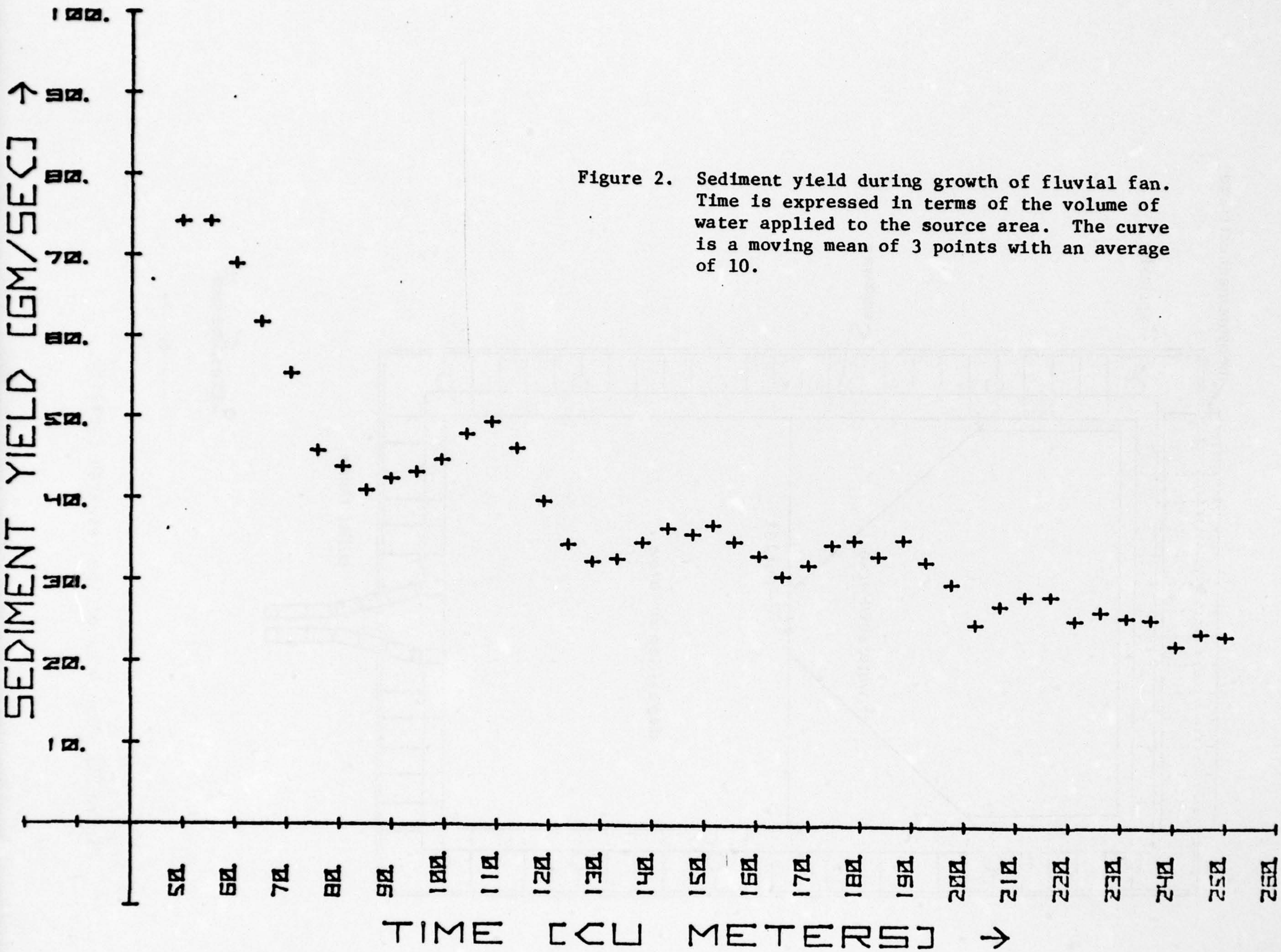

Figure 2. Sediment yield during growth of fluvial fan. Time is expressed in terms of the volume of water applied to the source area. The curve is a moving mean of 3 points with an average of 10.

areas and the subsequent migration of small headcuts into the main channel alluvium of the source area. However, even when sediment and water discharge decreased to a relatively constant value for the basin, there was frequent trenching of the fan head.

The trenching was not associated with the longer term sediment yield variations described above. Rather, the rapid spread of sediment and water over the unconfined apex region of the fan as it emerged from the source area, with the subsequent loss in velocity, caused a large percentage of this entrained sediment to be deposited at the fan head. The continuation of this process gradually produced a break in the source area-fan profile and an oversteepening of the alluvial deposit. This gradient increased to a critical or threshold value at which the tractive force required to re-initiate motion of the bed material was exceeded. As particles were eroded, the flow deepened and channelized, flow velocity and bed shear increased, further promoting sediment transport. This process, once initiated, resulted in fan-head trenching and the flushing of stored sediment from the head to the toe of the fan in well defined channels.

The end of a trenching cycle was when backfilling of the trench was complete. Sediment transported during the trenching process was deposited first in the lower reaches of the fan. As bars were formed, the broad, shallow channels migrated laterally over the lower and mid-fan regions. The locus of deposition moved up the fan surface as the channels gradually backfilled until the maximum deposition was once again concentrated at the apex. Between the downcutting events, flow was spread and sediment was deposited at the fan head, with very little deposition occurring on the distal fan surface.

Significantly, vertical accumulation and lateral growth of the fan was not continuous, as would be expected under conditions of constant sediment and water discharge. Rather, growth in any one area was incremental and controlled largely by frequent downcutting of the oversteepened fan head followed by relatively longer periods of lateral channel migration and channel backfilling in the mid-fan area. The locus of deposition shifted from apex to toe during fan head incision and from toe to apex as the channels subsequently filled with alluvium and vertical accretion once again was centered at the apex of the fan. During periods of entrenchment at the apex, the specific area of maximum deposition at the toe was largely controlled by the initial angle of incision and secondarily by areas of relatively lower elevation on the fan surface.

The progressive growth of the experimental alluvial fan was monitored qualitatively with time-lapse and 35mm photography and quantitatively by a grid of 225 pins, each representing the center of one square foot of the depositional surface. A series of computer generated depositional maps were produced from these data, and they provide a graphic representation of the shifting locus of deposition.

In order to quantify the changing patterns of deposition on the alluvial fan, a procedure was developed to integrate the effects of flow momentum and the initial angle of water and sediment discharge from the outlet of the source area. Probability analysis of the rates of erosion and deposition at various positions on the alluvial fan reveals that there is a high correlation between the magnitude of any given event and the magnitude of the following event at the same position, and between proximity to the apex and the magnitude of erosional or depositional events. Thus, for example, massive deposition events at the fan apex have a significantly greater chance of being followed by intense erosion (trenching) than do similar depositional events anywhere downfan. This framework provides for an overall identification of "risk" areas on the experimental fan and may help identify unstable situations in nature.

Having documented the growth of an experimental alluvial fan through a period of decreasing and then relatively uniform sediment discharge, a second phase of experimentation was initiated. The primary objective was to determine if incision of the fan that was induced by a significant reduction of sediment production in the basin would differ from the trenches that occurred during the previous period of constant sediment yield. Any morphologic differences could then be used as criteria for recognizing similar situations in the field.

To reduce the sediment yield reaching the fan, one foot squares of impermeable plastic (.5 ml thick) were placed on the drainage divides of the source area in increments of 5% of the total area of the drainage basin. Each "step" in the coverage of the sediment source area was retained for four hours of artificial precipitation during which time sediment samples were collected every ten minutes, and the surface grid of pins was measured at two hour intervals to note significant adjustments of the alluvial fan to the decreasing supply of sediment.

No significant or permanent trenching of the fan occurred until 35% of the drainage basin had been covered with the impermeable plastic. At that time a large trench formed in the mid-fan area and migrated headward into the main channel of the source area which was rejuvenated.

The formation of this trench was morphologically and dynamically different from those trenches that formed when a geomorphic threshold was exceeded. Of even greater interest was the amount of drainage area that required modification (35%) before the downstream area responded. This long delay in response was due to channel adjustment in the source area. As plastic sheets were added to the sediment source area and erosion on the interfluves was reduced, the streams maintained their sediment loads by channel and valley widening. Thus, the effect of the reduction of upland sediment production did not influence the fan until channel erosion no longer compensated for the reduced erosion of the interfluves. This observation, if confirmed by additional work, has significant implications for erosion control programs and indicates that the entire drainage system must be involved, not just the uplands. In fact, upland erosion control alone may precipitate a period of channel instability that will maintain the high sediment production by a drainage basin.

The sedimentology of the fluvial fan is extremely complex due to the several processes involved in building the deposit. The trenching of the fan adjusted the slope of the deposit by lowering the elevation of the fan head and shifting coarse material down fan. This adjustment resulted in the formation of wedge shaped deposits, thinning toward the fan apex. Although mean grain size within an individual layer of the deposit may decrease down fan the bulk sampling reflects an increase in relative importance of these layers in the distal direction, therefore, the mean size over what was the proximal part of the fluvial fan showed an increase in grain size in a down fan direction.

Internal fan stratigraphy was found to reflect the repeated development of channelized flow on the fan surface. The depositional units emplaced on the fan surface generally have a much higher degree of longitudinal continuity than lateral continuity. While deposition, during an isolated episode may take place over an entire longitudinal segment of the fan, lateral distribution is more restricted. Sedimentation did not progress over the fan at a constant rate. Changes in the sites of deposition were frequently not progressive, but altered position in an avulsive manner. Deposition often shifted from one position to another with large areas separating the two sites which were not subject to deposition during the abrupt change. Time lines within the deposit are, therefore, highly discontinuous laterally.

From examination of the latex peels taken of the fan it is apparent that the heavy minerals within the deposit occur in discreet stratigraphic horizons. The process of trenching, already discussed in relation to the development of the overall sedimentology and stratigraphy of the fan, was the decisive factor influencing the distribution of heavy minerals in the deposit. Some minor accumulations of heavy minerals occurred in the thalwegs of channels during normal deposition on the fan, but these are of secondary importance to those developed during the trenching phase of fan growth. Periods of fan-head trenching caused reworking of the fan apex and channel-fill alluvium of the source area while shifting and reconcentrating heavy minerals and coarse material down fan. Heavy mineral concentrations associated with channel-fill deposits within the fan also show a high degree of longitudinal continuity increasing toward the distal portion of the deposit and lateral discontinuity throughout.

There is an interesting agreement between the form of the heavy mineral concentrations of the experimental fan and those of the Precambrian quartz-pebble conglomerates of South Africa (Minter, 1976; Pretorious, 1974). That is, the heavy mineral concentrations are isolated in space, both vertically and laterally, due to the isolated nature of the trenching events during development of the fans.

Mudflow fans

A second series of fan experiments involved mudflow fan growth. Three arid-type or mudflow fans were produced, each by a series of discrete "storm" events of intense precipitation delivered to the source area. The location of the storm events within the source area was chosen randomly. Depending upon the relief of the area receiving the rainfall and the distance upstream from the fan apex, each event produced runoff of varying discharge and sediment concentration.

The first fan was derived from discharge events ranging from fluvial to mudflow in character. Incision of the fan apex was associated with several mudflow events that were followed by one or more erosive flows low in sediment concentration. Drainage density and relief of the source area were increased further during development of the second and third fans, and the great majority of precipitation events produced mudflows. As a result, fan surface topography became rougher, slopes were steeper and the growth patterns of the fans became more predictable. For example, deposition would typically concentrate on one side of the fan with the point of maximum deposition gradually shifting from the toe to the apex. Then, with deposition the dominant process at the fan head, the flows would shift abruptly to the distal portion of the opposite side of the fan and the process would repeat itself. The distance travelled by each mudflow in the down-fan direction was dependent on the viscosity of the sediment/water mixture and the magnitude of the event. Lateral growth of the fan was primarily controlled by these factors and only secondarily by the existence of a fan head trench. Extremely viscous mudflows were likely to be deposited within the apex region regardless of the presence of an incised channel that would carry less viscous flows to the lower or mid-fan regions.

Examination of latex peels taken of the mudflow-fan interior show a high degree of stratification preserved within the deposit. Internal organization in any coarse grained layer is poor but layers remain distinct. This is primarily due to the presence of layers of fine grained material deposited as the result of stream flow across the fan surface after each mudflow event. No distinct concentrations of heavy minerals could be observed within the layering although the amount of magnetite in the source area was the same as during the fluvial fan experiments. Comparison of the internal features of the alluvial fans shows that heavy mineral segregation within the fans decreased as the sediment concentration of the flow events increased. No major concentrations of magnetite are present due to the lack of continuous reworking of the alluvium within the rapidly aggrading fan-source area channel system.

The vertical stratigraphy shows a fine-grained basal layer followed by a coarsening-upward progradational sequence and a grain size discontinuity at the toe of the fan. Deposition of discrete lobes produced sheet-like layers covering broad areas of the fan surface. Thus, many of the individual strata at the fan head are more continuous in a radial direction in this fan than in the "wet" alluvial fan. A decrease in the extent of trenching of the mudflow fan allowed for greater preservation of these layers.

Trenching occurred frequently on the mudflow fan but it generally was the result of afterflow, and incision through more than one or two depositional layers was rare. This type of trenching acted only to breach the layer into which it incised, and it was a simple cut and fill process without major reworking of fan head sediments. No major rejuvenations of source area channels were observed, and these channels continued to aggrade throughout the experiment, thereby keeping pace with aggradation on the fan.

Sediment-yield variations

Previous experimental work in the DERF (Parker, 1977) dealing with aspects of evolving geomorphic systems has been concerned with the variation of sediment yield with time produced from an eroding sediment source.

In all experiments, a drop in the baselevel produced high sediment yields, which then decreased exponentially with time to a value indicative of little channel growth within the basin (Fig. 2). However, the variability about this "line" of exponential decay is large even during short time periods and with constant water application over a homogeneous mixture of eroding sediment. In order to determine the cause of these major variations and their possible relation to the threshold concept, two additional experiments were conducted. Detailed records of sediment yield from the DERF were recorded by weighing the progressive addition of all bedload material eroded from the drainage basin. Measurements of sediment discharge were taken every three minutes for over 113 hours of record, thereby yielding a nearly continuous set of data. Numerous channel cross sections and profiles were taken to monitor changes in geomorphic variables as the system evolved in time. The growth of the network was also recorded by 8 mm time-lapse photography.

The experiments were conducted in two parts. The first experiment consisted of a single lowering of baselevel (baselevel 1) with the subsequent headward growth of a drainage network. The second phase of the experimentation was similar to the first except baselevel was lowered after the dendritic drainage system had already been developed on the surface (baselevel 2). Rates of sediment discharge were thus compared with the previous experiment to distinguish differences between evolving and rejuvenated drainage networks, especially as related to changes in the sediment yield with time.

Data clearly show secondary peaks of sediment production that are due to temporary storage and flushing of sediment from the channels of the drainage network. Figure 3 illustrates the first of these peaks for both baselevels. The delay in the secondary peak of sediment yield associated with the rejuvenation of the existing drainage pattern likely reflects the greater potential storage capacity and lower slopes of the existing valley bottoms. Newly formed channel gradients were both less able to store sediment (i.e. less capacity and therefore more rapid storage and subsequent release), and they were closer to the slope threshold finally responsible for the flushing mechanisms (i.e., still a youthful, high gradient stream). These results confirm the existence of intrinsic geomorphic thresholds within the source area, during its erosional evolution, and the sediment yield variations, therefore, can be explained by the natural erosional processes that take place within the system (Patton and Schumm, 1975).

Episodic erosion

Prior to the development of the three arid-type alluvial fans, a preliminary study documenting the erosional evolution of a drainage network and the morphological development of its main channel (following a single lowering of baselevel) was carried out.

Beginning with a slightly concave source area, baselevel was lowered 46 cm. Sediment yield was measured and detailed profiles and cross sections of the developing channel were recorded with a digital point gage at 15 minute intervals.

As expected, incision progressed rapidly within the main channel, but the increasing sediment loads as the drainage system developed caused deposition on the floor of the valley. However, within 45 minutes decreasing sediment production in the headwaters as channel incision slowed triggered

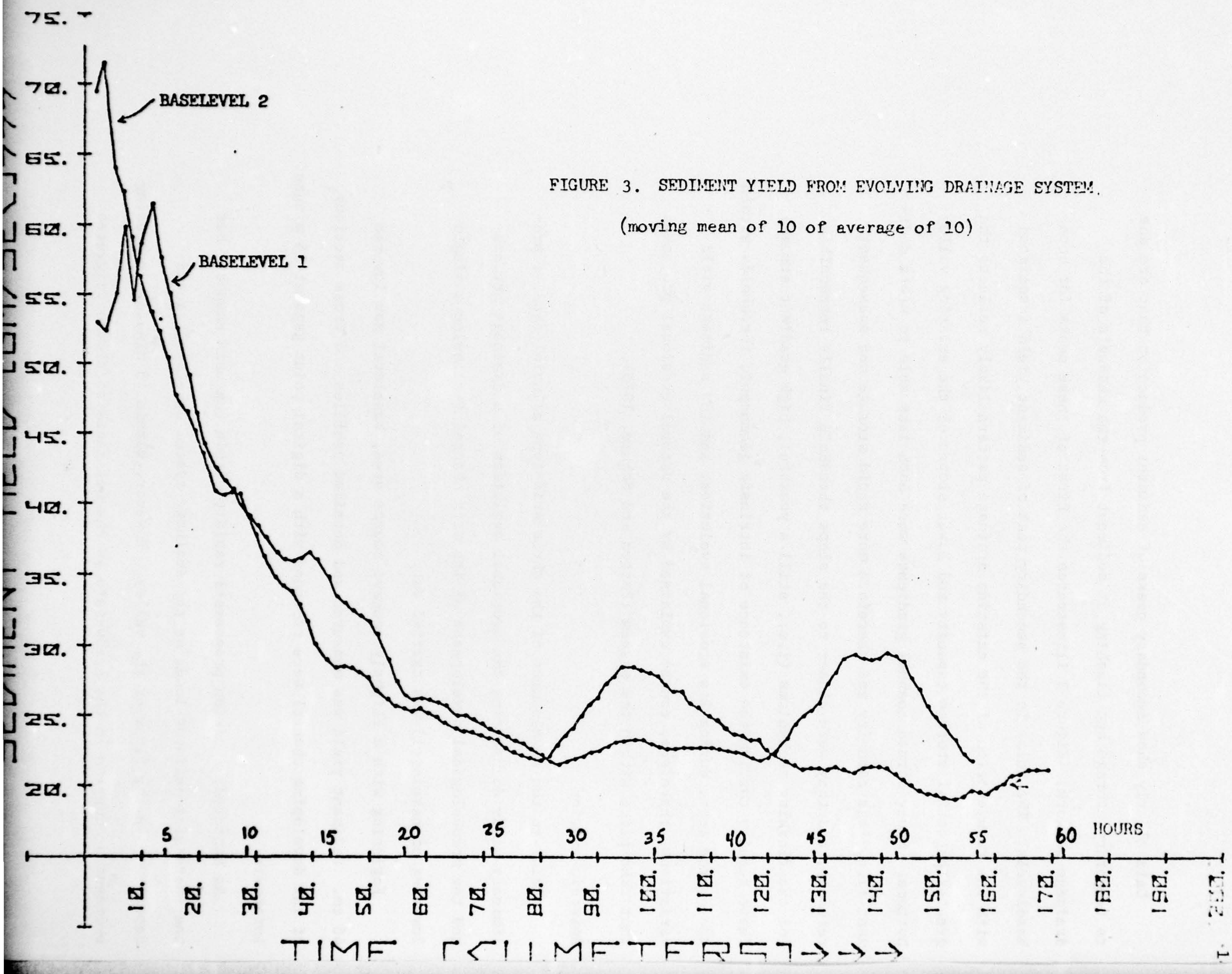

FIGURE 3. SEDIMENT YIELD FROM EVOLVING DRAINAGE SYSTEM.

(moving mean of 10 of average of 10)

a renewal of incision in the bedrock floor of the valley and a bedrock terrace formed (figure 4). In short, the rejuvenated channel did not incise progressively into the simulated bedrock. Rather incision was episodic with periods of incision separated by periods of channel stability or deposition (Weaver and Schumm, 1975).

Schumm and Parker (1973) and Schumm (1973) have reported a different type of terrace development associated with the complex response of a drainage network to a single lowering of baselevel. Both of these processes are of interest in that they reproduce what may happen in naturally or artifically rejuvenated river systems. That is, incision is not continuous, rather it is episodic. Results suggest that bedrock benches and high level gravel deposits in canyons as well as multiple cut-terraces elsewhere may have formed in response to expected sediment load variations following the rejuvenation of a drainage system. An appeal to such external influences as climate change or diastrophism is not always necessary or warranted. Field investigations of this phenomenon has demonstrated that in the Douglas Creek basin of northwestern Colorado multiple unpaired terraces formed during incision of the channel since 1888 (Womack and Schumm, 1977). Both the field and experimental work lead to new conclusions regarding the erosional development of a landscape (Schumm, 1976, 1977).

Field Investigations

Having documented the growth patterns, morphologic characteristics and internal sedimentologic and stratigraphic composition of four experimental alluvial fans (Weaver, 1977; Macke, 1977), a field phase of the research was initiated. In order to verify the experimentally demonstrated existence of a critical geomorphic threshold slope, which controls the inherent stability of a fan, two areas in the western U.S. were investigated to determine if geomorphic criteria could be developed to permit the recognition of incipiently unstable alluvial fans.

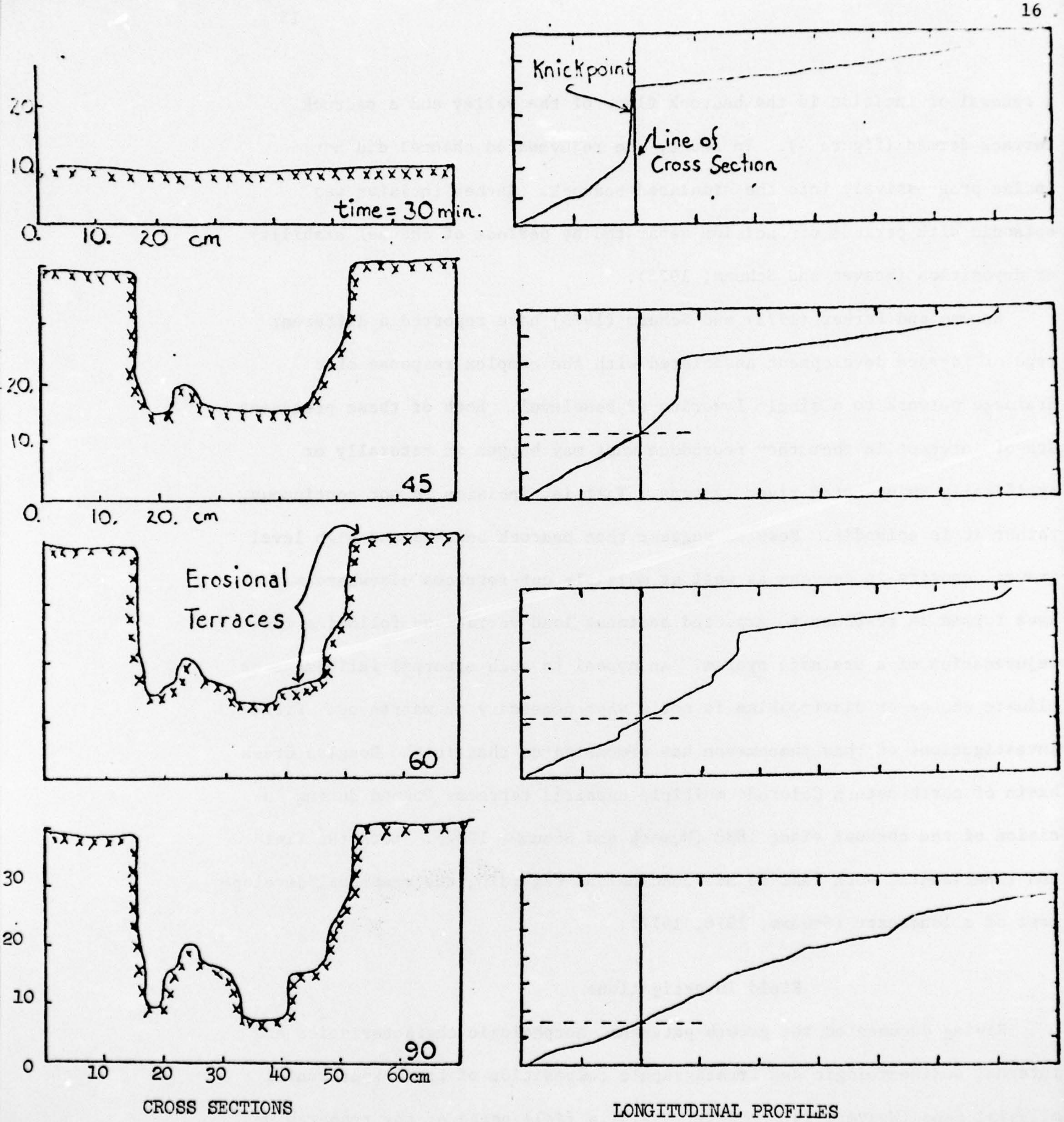

FIGURE 4. THE FORMATION OF MULTIPLE EROSIONAL TERRACES FOLLOWING A SINGLE LOWERING OF BASELEVEL

The first area is located adjacent to the Lemhi and Lost River Ranges east of Chalis, Idaho. Inspection of U. S. Geological Survey topographic maps of the region revealed approximately 15 to 20 fans, larger than 2.5 km^2. Of these, 18 were studied in three separate valleys. Of this sample slightly over half exhibited fan-head incision ranging from 5 to 35 meters in depth whereas the others, often immediately adjacent to the trenched fans, showed little or no indication of either confined flow or significant erosion.

Each fan surface was surveyed in the down-fan direction from the apex for at least 0.5 miles to record the fan-head slope. In the case of an untrenched fan, from one to three radial profiles were surveyed from the center line of the fan. In addition, profiles of the existing channel floor and major terraces as well as pace and hand level cross-sections of the main channels were surveyed.

Analyses of these and other data continues, but the observations suggest that, although the climate has changed significantly within the last 20,000 years, the fans have not responded to this alteration in the same manner. For example, on the northwest side of the Pahsimeroi Valley alluvial fans with identical source area geology display surface morphologies ranging from fan-head incision up to 35 meters deep and 360 meters wide to virtually unincised fan heads. The range of fan morphologies present in this one setting approaches the variability seen during development of a single experimental alluvial fan.

Examination of the relative position of the fans in the valley, their degree of entrenchment and the evidence of Quaternary tectonism indicates that the usual, simplistic view of change resulting from climate change, tectonism, etc. will not suffice. Based on the experiments the differences in fan morphology appears to be due to geomorphic threshold slopes which when exceeded, produce fan incision.

Other areas of the arid and semi-arid Southwest exhibit active fan building at the present time, but it is rarely possible to eliminate the other commonly recognized external forces as an explanation for fan entrenchment. One such area is the Cucamonga district of southern California, which is located along the southern boundary of the San Gabriel mountains approximately 30 miles east of Pasadena. The front of the range is cut by five major canyons and alluvial fans have developed along the base of the mountains. Slopes at the fan apices range from $1^{o}40'$ to $9^{o}05'$. Recent movement along the basin-bounding Cucamonga fault system is evident from the active fault traces in the fan gravels near the Day Canyon fan apex. However, in places this activity has been totally concealed by the rapid sedimentation still occurring on these active fans. Thus, the Deer Canyon fan shows no incision whatsoever. At the other extreme, the Cucamonga fan is incised some 20 meters with a wide flat-bottom channel transporting debris several miles down fan.

There is no field evidence that the dissection of the four entrenched fans developed simultaneously, thus apparently fan growth has not been a simple continuous process. This is further indicated by the presence of the Deer Creek fan which shows no incision and yet is centrally located in the study area. If uplift or some degree of tilting of the basin margin was thought to be responsible for the fan-head incision on the other fans then the Deer Creek fan should have reacted in a similar manner.

In light of the extreme morphologic variability of alluvial fans, which have developed under seemingly similar climatic and tectonic conditions, the control of fan-head incision by threshold fan slopes seems evident.

Summary

Both the experimental and field phases of the project indicate that geomorphic thresholds exist and that this concept can be of significance in the recognition of incipiently unstable, components of the landscape. For example, within a given region, valley floor slopes, alluvial fan slopes and channel sinuosity usually vary over an order of magnitude. It should be possible to identify at what range of slopes the landforms are unstable and subject to major erosional or depositional change, as a result of a triggering hydrologic event or due to man's intervention. This approach was used in an examination of the alluvial valleys of the Piceance Creek basin, northwestern Colorado and within this region of similar geology, climate, and land use a critical slope was recognized above which gullying occurs (Patton and Schumm, 1975). The geomorphic approach to the recognition of potentially unstable landforms is the result of the research performed under the present and previous Army Research Office projects.

It is clear that the results of this project have a significant contribution to make not only in the development of preventive conservation but also to river control engineering. For example, if a river reach has altered due to its high sinuosity, an appropriate control measure would be to attempt to decrease the gradient of the channel by restoring some degree of sinuosity to the channel. The assumption is that channel sinuosity will increase to a threshold value at which time cutoffs occur naturally or avulsion takes place. Recently the geomorphic threshold concept has been used to explain the pattern and high sediment delivery from the Chippewa River of Wisconsin into the upper Mississippi River (Schumm and Beathard, 1975). Apparently in prehistoric times the Chippewa River changed its meandering pattern and position by avulsion. Geomorphic evidence indicates that if the course of the lower Chippewa were to attain a sinuosity of 1.25 much of the sediment now eroded from the bed and banks of this unstable channel would be stored within the valley. This should significantly reduce the sediment problems in Pool 4 of the Mississippi River below Lake Pepin. It may be that reduction of sediment load to the Mississippi River can be achieved by restoring a degree of sinuosity to the Chippewa channel that, according to geomorphic evidence, will be stable in a meandering configuration.

The geomorphic approach was also used by civil engineers studying the Gros Ventre River, Wyoming. They concluded after consultation within the principal investigator that no structural controls were needed to restore the sinuous thalweg of that river, which had been destroyed by a major flood. The river is now reverting slowly and naturally to a more sinuous channel of the type desired by the Wyoming Fish and Game Department. The geomorphic approach requires an understanding of landform history, which can provide a basis for working with the natural system in order to accomplish conservation or river stability goals. This may be a significant advance in man's dealings with the landscape.

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